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EXPERIMENTAL NEUTRINO PHYSICS

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The current experimental status of neutrino physics is reviewed. It contains the evidences for a non-vanishing neutrino rest mass from neutrino oscillation searches. In addition an outlook is given on determining the various mixing matrix elements and mass differences more precisely with new experiments. Of special interest is the value of the mixing angle θ_{13} determining the possibility of detecting leptonic CP violation in the future. The prospect for absolute mass measurements using beta and double beta decay as well as cosmological observations is presented.

Keywords: neutrinos; neutrino mass; neutrino oscillation

1. Introduction

In the last decade convincing evidence has been found for a non-vanishing rest mass of neutrinos. If neutrinos are massive the weak and mass eigenstates are not necessarily identical, a fact well known in the quark sector where both types of states are connected by the CKM-matrix. This would allow for a similar mixing matrix in the leptonic sector called PMNS-matrix and for the phenomenon of neutrino oscillations, a kind of flavour oscillation, which is already known in other particle systems.

2. Evidence for neutrino oscillations and tests in the near future

Currently we have three evidences for neutrino oscillations coming from accelerators, the atmosphere and the Sun. All evidences will be discussed in a two flavour scenario, where the mixing is described by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \tag{1}$$

with θ as the mixing angle, analoguous to the Cabibbo angle in the quark mixing matrix. The oscillation probability for one neutrino flavour ν_α into another one ν_β is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2(1.27\frac{L \times \Delta m^2/eV^2}{E/MeV})m \tag{2}$$

with $\Delta m^2 = m_j^2 - m_i^2$ as the difference of two mass eigenstates $m_{i,j}$, L the distance from the neutrino source to the detector and E the neutrino energy.

2.1. *The LSND-evidence*

The LSND experiment at LANL was a 167 t mineral oil based liquid scintillation detector using scintillation and Cerenkov light for detection. It consisted of an approximately cylindrical tank 8.3 m long and 5.7 m in diameter. LSND took data from 1993 - 1998. For the "decay at rest" analysis in the channel $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, the signal reaction was

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{3}$$

As experimental signature a positron within the energy range 20 MeV $< E_e <$ 60 MeV together with a time and spatial correlated delayed 2.2 MeV photon from p(n,γ)D is required. After background subtraction indeed an excess of $87.9 \pm 22.4 \pm 6.0$ events was observed [1]. Interpreting those events as oscillation signal it would correspond to a transition probability of $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 2.64 \pm 0.67 \pm 0.45 \times 10^{-3}$. With rather similiar parameters the KARMEN experiment was operated at Rutherford Appleton Laboratory from 1990 to 2001, finding no evidence for an oscillation signal [2] (see figure 1) . To which extent both experiments are in agreement or not is a severe statistical problem. A combined analysis on both data sets has been performed [3]. Two regions remain where both experiments are compatible with a positive effect, one at $\Delta m^2 \approx 7eV^2$ and one with $\Delta m^2 < 1eV^2$.
With the Δm^2 region known, it is possible to perform a new experiment to test this evidence. The experiment MiniBooNE at Fermilab is exactly doing that. The neutrino beam is produced by the Fermilab Booster, sending a high intensity pulsed proton beam of 8 GeV on a Be-target. The positively charged secondaries, mostly pions, are focused by a magnetic horn and brought into a decay tunnel. This results in an almost pure ν_μ beam (ν_e contamination less than 0.3 %). The detector itself is installed about 500m away from the end of the decay tunnel. It consists of 800 t of pure mineral oil, contained in a 12.2 m diameter spherical tank. A support structure carries about 1550 phototubes for detection of Cerenkov and scintillation light. To explore the LSND evidence to a level of 5σ about 10^{21} protons on target are required (see figure 1). More than 30 % of the data have been obtained and by 2005 first results can be expected.

2.2. *Zenith angle dependence of atmospheric neutrinos and K2K*

For more than a decade it is known that the ratio of electron/muon like events observed from atmospheric ν_e and ν_μ neutrinos does not agree with Monte Carlo expectation. A much deeper understanding has been obtained with the advent of Super-Kamiokande, which is able to perform a measurement of the zenith angle distribution of both flavours separately (figure 2) . From that it can be concluded that the reason for the deviation in the ratio is due to a lack of muons, or more

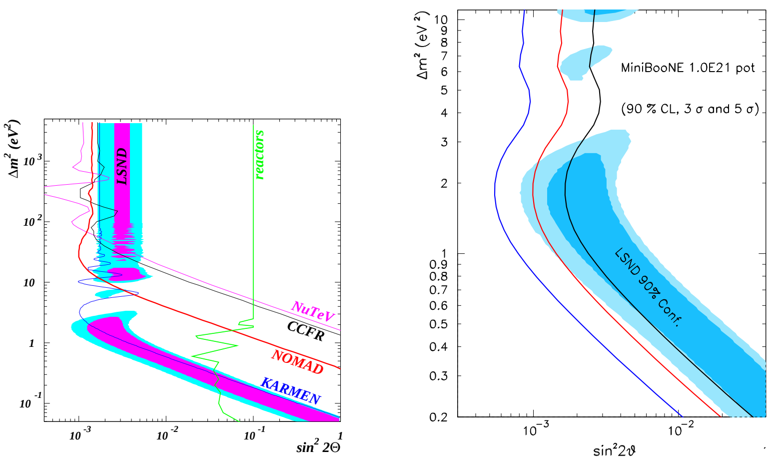

Fig. 1. Left: $\sin^2 2\theta$ - Δm^2 plot showing the parameter regions describing the LSND observation (purple, blue). Exclusion curves from various other experiments are shown as well, with the region on the right side excluded (from [4]). Right: In case of a non-observation of an effect in MiniBooNE the regions on the right side of the curves can be excluded with the shown significance.

precisely, the number of upward going muons is reduced, an effect to be explained by neutrino oscillations including the ν_μ . An involvement of ν_e could be excluded by the CHOOZ and Palo Verde reactor experiments. The parameters determined [5] are in agreement with maximal mixing and a Δm^2 of $1.3 - 3 \times 10^{-3}$ eV^2. Recently, Super-Kamiokande has published a high resolution L/E analysis [6], showing a better sensitivity to the involved Δm^2 . The outcome is a range of parameters as $1.9 \times 10^{-3} eV^2 < \Delta m^2 < 3.0 \times 10^{-3} eV^2$ and $\sin^2 2\theta > 0.90$ with 90 % CL and a best fit value of $\Delta m^2 = 2.4 \times 10^{-3} eV^2$ and $\sin^2 2\theta = 1.02$ (figure 3).
Independently the result is confirmed by the K2K experiment shooting a neutrino beam from KEK to Super-Kamiokande with a baseline of 235 km. The current analysis [7] is based on 8.9×10^{19} protons on target and shows a clear deficit in muon neutrinos (57 observed with 84.8 expected) suggesting a parameter region as shown in figure 3.
figure Further long baseline experiments will be online soon, the next one is MINOS. This 5.4 kt magnetised iron spectrometer is located in the Soudan mine in Minnesota using a neutrino beam from Fermilab. The baseline is 732 km and a low energy beam profile has been chosen first to have a good sensitivity for a disappearance search. The detector is already operational and first beam is expected by end of 2004. The European program, using a neutrino beam from CERN to the Gran Sasso Underground Laboratory in Italy is focussed on an optimized ν_τ appearance search which implies a higher beam energy. Two experiments, ICARUS and OPERA, are currently installed for the search. ICARUS will be a 3 kt LAr TPC working like an electronic bubble chamber and ν_τ detection relies on the different distributions

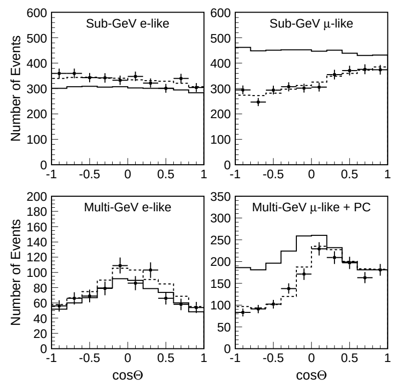

Fig. 2. Zenith angle distribution of electrons (left) and muons (right), both divided into low and high energy samples. Clearly visibile is the deviation from Monte Carlo expectations (solid line) and data points in the muon sample, especially for those coming from below ($\cos\theta < 0$. The dotted curve corresponds to a fit including neutrino oscillations (from [5]).

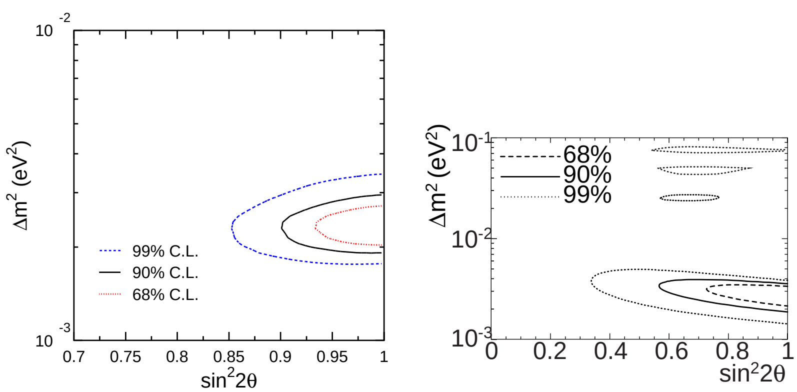

Fig. 3. Left: Contours obtained by the recent L/E analysis in Super-Kamiokande (from [6]). Right: Countours as obtained by K2K. Both are in reasonable agreement pointing towards and Δm^2 between 2-3 $\times 10^{-3} eV^2$ and maximal mixing (from [7]).

of kinematic variables in ν_μ and ν_τ charged current reactions [9]. The basic building blocks of OPERA are sandwich sheets of lead and emulsions combined to form 8.3 kg bricks. In total more than 200000 bricks will be installed [10]. The excellent spatial resolution of emulsions allows to search for kinks within tracks, a characteristic feature of ν_τ interactions. The data taking is foreseen to start in 2006 and within 5 years both experiments should collect about a dozen τ candidates.

2.3. *Solar and reactor neutrinos*

Big progress has been achieved in the field of solar neutrinos. The problem of missing solar neutrinos has been solved by the Sudbury Neutrino Observatory (SNO)

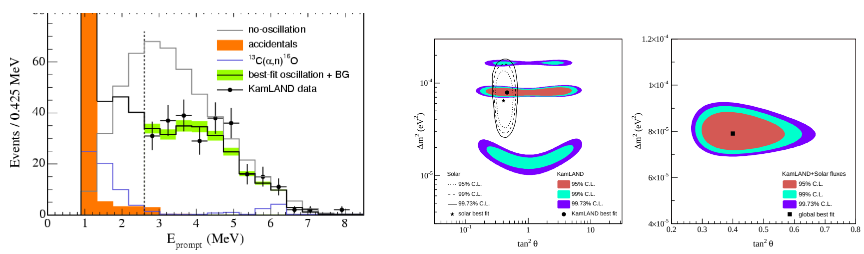

Fig. 4. Left: Prompt energy spectrum as observed by KamLAND. A clear spectral distortion can be seen. Right: Combined KamLAND and solar data fits (from [11]).

measuring in their flavour-blind neutral current reaction on the deuteron the expect flux from solar models [8]. Combined with all the other solar neutrino observations from Super-Kamiokande , Homestake and the gallium experiments SAGE and GALLEX/GNO the parameter range could be pinned down to the large mixing angle solution, showing that matter oscillations are responsible for the deficit in solar ν_e . The current best fit value combining all solar data is at $\Delta m^2 = 6.46 \times 10^{-5} eV^2$ and $\tan^2\theta = 0.4$.

Table 1. Current results of solar neutrino experiments. Radiochemical results are given in SNU, fluxes from water Cerenkov detectors in units of $10^6 cm^{-2} s^{-1}$.

Experiment	Target	Result	Prediction
Homestake	^{37}Cl	2.56± 0.23	7.6 ± 1.2
GALLEX/GNO	^{71}Ga	69.3± 5.5	127 ± 10
SAGE	^{71}Ga	$66.9^{+5.3}_{-5.0}$	127 ± 10
Super-K	H_2O	2.35± 0.10	5.1 ± 0.2
SNO	D_2O	5.21 ± 0.47	5.1 ± 0.2

Completely independent information is coming from KamLAND, a long baseline experiment using nuclear power plants. The KamLAND experiment is a 1000 t Liquid Scintillator located at the former position of the Kamiokande detector in Japan. After 515 days of data taking (766 ton × yr exposure) they see a clear spectral distortion and deficit of events [11]. The spectral distortions are very sensitive to Δm^2 resulting in $\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$ hence the parameter space in combination with solar neutrinos in a global fit could be further reduced to $\tan^2\theta = 0.40^{+0.10}_{-0.07}$ (figure 4).

To summarize, three evidences for neutrino oscillations exist:

- The LSND-evidence, $10^{-3} < \sin^2 2\theta < 10^{-1}$, $0.1 eV^2 < \Delta m^2 < 6 eV^2$, ν_μ - ν_e
- The atmospheric zenith angle dependence $\sin^2 2\theta = 1.00$, $\Delta m^2 = 2.4 \times 10^{-3} eV^2$, ν_μ - ν_X
- Solar and reactor neutrinos, $\sin^2 2\theta \approx 0.81$, $\Delta m^2 = 7.9 \times 10^{-5} eV^2$, ν_e - ν_X

However, it is obvious that if all of them are correct, more neutrinos are needed, because of the unitarity of the mixing matrix, which only allows to form two independent Δm^2 . In combination with the LEP bound of three light neutrinos, those possible new neutrinos cannot participate in the standard electroweak interactions and hence are called sterile.

3. The determination of the elements of the full 3x3 mixing matrix

The discussion of atmospheric and solar neutrinos in a two flavour scenario is justified by the fact that the mixing angle $\sin^2\theta_{13} < 0.12$ (90% CL) at $\Delta m^2 \approx 3 \times 10^{-3} eV^2$ as measured by the reactor experiments CHOOZ and Palo Verde. However, the knowledge of its precise value and especially if it is non zero is extremely important, because only in this case it would allow the possibility to search for CP-violation in the lepton sector. In the full three flavour mixing scenario the mixing matrix U (called PMNS-matrix) is given by

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{4}$$

where $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$ $(i, j = 1, 2, 3)$. In addition to the normally occuring CP-phase, there can be two more CP-violating phases α_1, α_2 associated with a possible Majorana character, which do not show up in oscillations but can have an effect in neutrinoless double beta decay. The new matrix would be $U = U_{PMNS}\times$ diag $(1, e^{i\alpha_1}, e^{i\alpha_2})$. As can be seen from eq. 4 the CP-phase is always showing up in combination with $\sin\theta_{13}$, which will ultimately determine the sensitivity for CP-violation searches.

The precise oscillation probabilities in the three flavor scenario including matter effects are quite complex (see e.g. [12,13]). One major result is the 8-fold degeneracy in parameters describing a specific oscillation probablility, namely the degeneracy within the pairs $\delta - \sin 2\theta_{13}, \delta - sign\Delta m^2_{13}$ and $\theta_{23} - (\pi/2 - \theta_{23})$.

The first step towards a search for a CP-violation will be a determination of θ_{13}. Currently two strategies are followed, either using off-axis accelerator beams or performing a very precise new reactor experiment. A degeneracy of neutrino parameters in off-axis beams makes a measurement at reactors desirable to disentangle the various parameters and break their degeneracy.

A determination of θ_{13} at reactor search is coming from the survival probability

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2\theta_{13}\sin^2(1.27\frac{\Delta m^2_{13}L}{E}) \tag{5}$$

Taking the current oscillation evidences a baseline of about 1-2 km would show the maximum sensitivity. The precision required including especially systematic effects, is pushing towards a two detector concept. A compilation of discussed options and sites is shown in tab. 2.

Table 2. Proposed sites and parameters for considered reactor experiments to measure θ_{13}.

Site	Power ($GW_{thermal}$)	Baseline (Near/Far) m	Shielding (Near/Far) mwe	Sensitivity (90 % CL)
Krasnoyarsk, Russia	1.6	115/1000	600/600	0.03
Kashiwazaki, Japan	24	300/1300	150/250	0.02
Double Chooz, France	8.4	150/1050	30/300	0.03
Diablo Canyon, CA	6.7	400/1700	50/700	0.01
Angra, Brazil	5.9	500/1350	50/500	0.02
Braidwood, France	7.2	200/1700	450/450	0.01
Daya Bay, China	11.5	250/2100	250/1100	0.01

In addition to nuclear power plant searches, there is the option to use accelerator neutrino beams off-axis. The important point to notice here is the fact that due to the pion decay kinematics by going slightly off-axis the obtained neutrino energy is basically independent from the original pion energy. Both are related via $E_\nu = 0.43 E_\pi/(1+\gamma^2\theta^2)$ with θ as the off-axis angle. Thus, one can obtain a narrow band beam at the expense of intensity. The neutrino beam energies discussed are around 1 GeV and below. Here another important point enters, namely the precise knowledge of cross sections. In this regime quasi-elastic scattering dominates with contributions from resonance production, coherent particle production and diffractive interactions. A new proposal to accurately measure those cross-sections MINERvA at Fermilab. In addition, to get a good understanding of the beam also the pion, kaon production in the target has to be known precisely. Experiments like HARP, NA49, MIPP have already obtained data or will do so in the near future. Two proposals exist for off-axis beams, Nova and T2K, with the latter being approved. While Nova plans to use the NuMI beam at Fermilab, T2K will be using the new accelerator facility in Tokai (Japan) to shoot a beam towards Super-Kamiokande. In a second step this can be extended to a higher beam energy and a larger detector (Hyper-Kamiokande). In addition to these superbeams, i.e. conventional neutrino beams with a high intensity, two completly new beam concepts are envisaged as well. The first one is called beta beams. The idea is to accelerate β-unstable isotopes [14] to energies of a few 100 MeV using ion accelerators like ISOLDE at CERN. This would give a clearly defined beam of ν_e or $\bar{\nu}_e$. Among the favoured isotopes discussed are ^{6}He in case of a $\bar{\nu}_e$ beam and ^{18}Ne in case of a ν_e beam. The second one is a muon storage ring ("neutrino factory"). The two main advantages are the precisely known neutrino beam composition and the high intensity (about 10^{21} muons/year should be filled in the storage ring). Even if many technical challenges have to be solved, it offers a unique source for future accelerator based neutrino physics. First experimental steps towards realisation are the HARP experiment at CERN, which determines the target for optimal production of secondaries, the study of muon scattering (MUSCAT experiment) and muon cooling (MICE experiment).

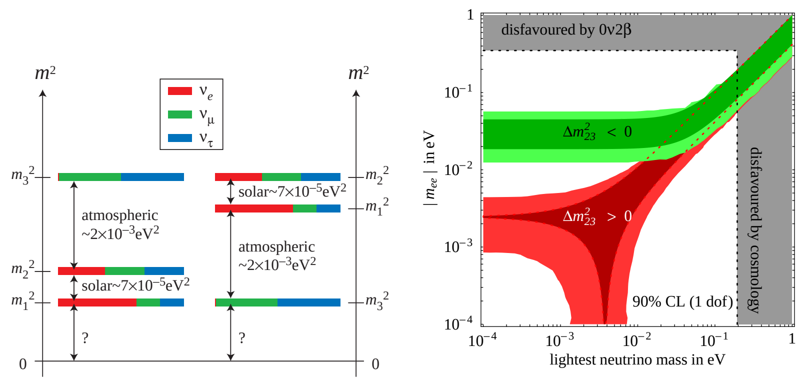

Fig. 5. Left: Possible configurations of neutrino mass states as suggested by oscillations. Currently a normal (left) and an inverted (right) hierarchy cannot be distinguished. The flavour composition is shown as well. Right: The effective neutrino mass as a function the lightest neutrino mass state. As can be seen hierachical structure only occur for mass well below 100 meV. If neutrino masses are above they are almost degenerated (from [15]).

4. Absolute neutrino mass measurements

Neutrino oscillations are no absolute mass measurements and thus allow for various configurations of the mass eigenstates and mass models. Taking the small Δm^2 involved, for an absolute neutrinos mass above about 0.1 eV the neutrino mass states will be almost degenerated. However as function of the lightest mass eigenstate m_1 the two hierarchical models can be distinguished for lower masses with the help of double beta decay (figure 5). Currently three types of absolute mass determinations are explored, which have parts in common but on the other hand also differences.

4.1. *Beta decay*

The precise investigation of the endpoint of the electron energy spectrum in tritium beta decay is the classical way to search for a non-vanishing rest mass of the neutrino. Within the last decade due to new spectrometer developments two groups from Mainz and Troitzk were able to deduce an upper limit on the neutrino mass of m_ν <2.2 eV (95 % CL). The actual measured quantity in the presence of mixing is

$$m^2_{\nu_e} = \sum_i \mid U_{ei} \mid^2 m^2_{\nu_i} \tag{6}$$

A next generation of spectrometer, scaled in size to be sensitive to 0.2 eV, is KATRIN [16], currently under installation in Germany. It will start data taking in 2008. Two alternative ideas are the search using the beta emitter ^{187}Re in compounds as cryogenic bolometers. The advantage is the very low Q-value of ^{187}Re of only about 2.5 keV. In addition, if a newly observed line in ^{115}In is due to a beta-decay into an excited state, here the endpoint energy would be only about 2 eV.

4.2. *Neutrinoless double beta decay*

A different process related to neutrino masses is double beta decay. Of special importance is the neutrinoless decay mode

$$(Z, A) \rightarrow (Z+2, A) + 2e^- \tag{7}$$

which violates total lepton number by two units and requires massive Majorana neutrinos and hence has sensitivity to the fundamental character of neutrinos in contrast to beta decay. The experimental observable is a half-life which can be linked to the neutrino mass as

$$(T_{1/2})^{-1} = G^{0\nu}(Q, Z) \mid M^{0\nu}_{GT} - M^{0\nu}_{F} \mid^2 (\frac{\langle m_{\nu_e} \rangle}{m_e})^2 \tag{8}$$

with $G^{0\nu}(Q, Z)$ as the well known phase space factors and $\mid M^{0\nu}_{GT} - M^{0\nu}_{F} \mid^2$ as the involved nuclear matrix elements. The latter are a severe source of uncertainty. The measured quantity is called effective Majorana neutrino mass and given by

$$\langle m_{\nu_e} \rangle \ = \mid \sum_i U^2_{ei} m_i \mid = \mid \sum_i \mid U_{ei} \mid^2 e^{2i\alpha_i} m_i \mid \tag{9}$$

The current situation is dominated by a hot debate of a claimed evidence (figure 6), as been observed with Ge-semiconductor detectors [17]. The claimed half-life region of and the corresponding neutrino mass of would clearly show that neutrinos are almost degenerated. Currently two large-scale experiments are running, CUORICINO and NEMO-3. The first one is using 40 kg of TeO_2 as cryogenic bolometers and neutrino mass limits in the range have been obtained [18]. NEMO-3 is a TPC based detector using 10 kg of foils, dominantly ^{100}Mo, for the search and first results have been published recently [19]. Both experiments plan to upgrade their detectors towards larger masses. Of course there are further proposals and ideas for future experiments. Two proposals using enriched ^{76}Ge are GERDA and MAJORANA. The first one is in a good situation to probe the claimed evidence in a reasonable short time, by having the Heidelberg-Moscow and IGEX enriched Ge-detectors at their hands. EXO, a He-filled TPC, focussing on the decay of ^{136}Xe has 200 kg of enriched Xe and plans to start measurement soon. COBRA [20], by using CdZnTe detectors the only other semiconductor approach besides Ge, is operating several detectors at Gran Sasso Laboratory and has an enhanced sensitivity to double electron capture and double positron decays as well. A compilation of proposed experiments can be found in [13].

4.3. *Neutrino masses from cosmology*

During the last decade enormous progress has been made in observational cosmology and the precision of current data allows to put some limits on neutrino masses. According to standard cosmology, in connection with the 3K cosmic microwave

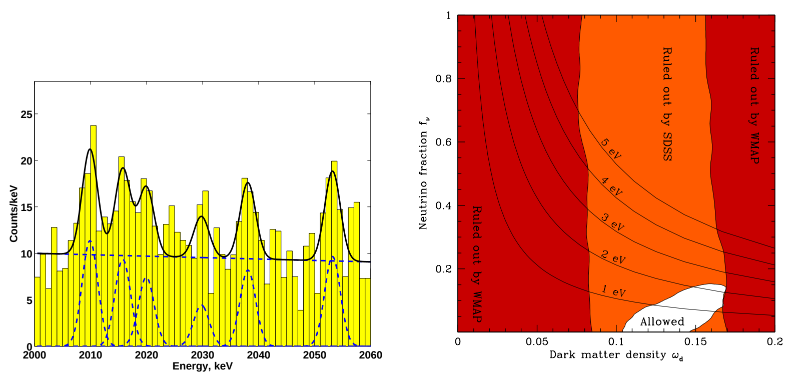

Fig. 6. Left: Sum energy spectrum in the region around the double beta peak of ^{76}Ge at 2039 keV as obtained by the Heidelberg-Moscow experiment(from [17]). Right: Neutrino mass fraction versus dark matter density as an example of correlations among cosmological parameters. As can be seen the allowed range is up to about the laboratory values (from [24]).

background (CMB) there should exist a 1.96 K relic neutrino background. Taking the particle densities of both the well known relation for the density

$$\Omega_\nu h^2 = \frac{m_{\nu,tot}}{94eV} \tag{10}$$

can be obtained. Hence by measuring $\Omega_\nu h^2$ the sum of all three neutrino masses can be obtained. Taking the upper limit from tritium beta decay and the oscillation results, neutrinos can still contribute up to 15 % of the total density. Cosmological bounds basically stem from large scale structure surveys. Neutrinos, being relativistic particles, at the beginning of structure formation effectively washed out small scale perturbations. Hence, the net result is less small scale objects and thus a suppression in the power spectrum given by [21]

$$\frac{\Delta P(k)}{P(k)} \approx -8\frac{\Omega_\nu}{\Omega_m} \tag{11}$$

should be observed. However, all mass bounds obtained are depending on the cosmological model used. Currently the standard lore is a ΛCDM model with adiabatic linear perturbations. In addition, the other cosmological parameters have to be known, currently determined by CMB observations. The reason is that there is a strong correlation of Ω_ν with other cosmological parameters [22]. Depending on the assumptions and data used limits on the neutrino mass between 0.3-3 eV have been obtained [23], even a non-vanishing rest mass could be obtained showing the strong dependence on the assumptions. A comprehensive recent analysis on CMD and SDSS data can be found in [24]. To sum it up, it is fair to say, that cosmological bounds achieved the same level of sensitivity as laboratory experiments. In the future the comparison of all three areas, beta decay, neutrinoless double beta decay and cosmological mass determinations will improve and it will be very exciting to explore their consistency and gain further information on the neutrino mass.

Summary and conclusion

Neutrino physics has made major progress over the last decade. A non-vanishing rest mass has been established in oscillation experiments. The solar neutrino problem is solved in being due to matter oscillations, independently confirmed by nuclear reactor searches. However, the three evidences do not all fit together and if all are true, more neutrinos than those from the Standard Model are needed. The next step will be to more precisely determine the elements of the full 3x3 mixing matrix, ultimately trying to detect CP-violation in the leptonic sector. The first step to do is a more precise determination of the angle θ_{13} in nuclear reactor searches and off-axis beams.
Neutrino oscillations do not determine the absolute mass scales. For that beta decay, neutrinoless double beta decay and cosmological studies can be used. In all three areas major progress has been achieved and can be expected in the next decade.

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